Chapter 6

Collection Systems

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Introduction

Stormwater and wastewater collection systems are a critical link in the urban water cycle, especially under wet-weather conditions. In the context of pollution control, these systems transport sanitary wastewater, stormwater, industrial wastewater, non-point source pollution, and inflow/infiltration (I/I).

Research in the area of collection systems as a means of wet-weather pollution control is showing signs of renewed activity, especially in Europe and Japan (Henze et al. (1997), Sieker and Verworn (Ed.) 1996, Ashley (Ed.) 1996, Bally et al. (Ed.) 1996). Case studies of recent applications of innovations in this country are also receiving attention, as evidenced by recent Water Environment Federation technical conferences (WEF 1994a, 1994b, 1995a, 1995b, 1996) and a recent EPA seminar (USEPA 1996b). By applying new technology and revisiting traditional urban water problems with a fresh outlook, advances are being made in a wide variety of sewer related areas. By reviewing successful applications of research in recent projects, a vision of successful wet-weather management of collection systems of the future may be formulated.

An historical review of collection systems in the U.S. helps with understanding the problems associated with modern sewer collection systems. Many of the early sewers, including some from before the turn of the century, are still in service. As cities grew, the need for stormwater and wastewater conveyance became a necessity to protect human health. Stormwater and sanitary waste were generally conveyed to the nearest natural water body. In fact, the modern word “sewer” is derived from the old English word meaning “seaward” (Gayman 1996).

In the late nineteenth and early part of the twentieth century, these conveyance systems were “intercepted” into a smaller conveyance sized to accommodate a multiple of the estimated dry weather sanitary flow (Moffa 1990, Foil et al. 1993, Metcalf and Eddy 1914). The first construction of an intercepting combined sewer in this country was in Boston in 1876 (Foil et al. 1993). The intercepted sewage was usually transported to a primitive treatment plant consisting of solids and floatables removal via screening and settling (Metcalf and Eddy 1914).

During this period there was considerable debate between proponents of separate systems and those who favored CSS. The appeal of the combined system was one of economics, especially in areas where rainfall intensity was high enough to regularly flush the sewers, greatly alleviating the need for regular cleaning (Metcalf and Eddy 1914). While engineers in England were strongly advocating separate systems as early as 1842, primarily for sanitation reasons, engineers in America were divided. An important engineering monograph of the time by Dr. Rudolph Hering is quoted in "Design of Sewers" by Metcalf and Eddy (1914):

> ***The advantages of the combined system over a separate one depend mainly on the following conditions: Where rain-water must be carried off underground from extensive districts, and when new sewers must be built for the purpose, it (combined sewers) will generally be cheaper. But more important is the fact that in closely built-up sections, the surface washings from light rains would carry an amount of decomposable matter into the rain-water sewers, which, when it lodges as the flow ceases, will cause a much greater storage of filth than in well-designed combined sewers which have a continuous flow and generally, also, appliances for flushing.***

Thus problems associated with settled solids (e.g., maintenance costs and odor problems) were a primary reason for the spread of combined sewers in this country at the turn of the century.

Separate systems were advocated for areas with potable water concerns. Perhaps the "link" between wastewater and stormwater with drinking water in the urban water cycle was more evident under early 20th century conditions, when pumping costs were too great to accept the volume of combined sewage, and when rainwater did not require removal (Metcalf and Eddy 1914). One of the first separate systems designed in this country was in Memphis, TN following a yellow fever outbreak in 1873 when more than 2,000 persons died. Unfortunately, this system was apparently designed without regard to English experience and had significant design problems associated with it (Metcalf and Eddy 1914, Foil et al. 1993).

Separate sewer systems became more widely accepted as receiving water quality decreased and potable water supplies were threatened. They were designed primarily for newer urban areas, but later were also used as a means of doing away with combined systems. Separate systems, consisting of sanitary and storm sewers, remain the norm in the U.S.

However, NPS pollution has become more of a concern for urban areas (as well as in rural agricultural areas), separate untreated stormwater conveyance is now being questioned as an acceptable design practice. For example, sewer separation, a common mitigative action for areas with severe CSO problems, has been shown in some areas to be an infeasible solution for reducing water quality impacts. In Cincinnati, OH separation of the combined system was evaluated as a design alternative and shown to be an ineffective means of controlling the total solids load to the receiving water due to the polluted stormwater runoff from the untreated separate storm sewers (Zukovs et al. 1996). Conversely, separation has been an effective CSO abatement alternative in other urban areas (e.g., Minneapolis, MN). These cases indicate the site specificity of runoff, specifically with regard to land-use density and local rainfall characteristics. Clearly, a new look at some of these age old urban water management problems is in order.

Skokie, IL offers one example of a “new look.” Faced with a massive basement flooding problem caused by combined sewer surcharging, Skokie found traditional sewer separation to be technically feasible but unacceptably costly. Accordingly, controlled on and below street storage of stormwater was found to be a cost-effective (one-third the cost of separation) solution. Flow and storage control is achieved with a system of street berms and flow regulators. The premise of this retrofit system, which is almost completely implemented throughout the 8.6 square mile community, is that “out of control” stormwater is the root cause of combined sewer problems. As a side benefit, the Skokie system includes numerous pollutant-trapping sumps (Walesh and Carr 1998).

Problems Commonly Associated with Present Day Collection Systems

As described above, some collection systems in use today in the U.S. represent over 100 years of infrastructure investment. During that period the technical knowledge of the nature of wastewater has increased and the public expectation of the performance and purpose of collection systems has changed. What was considered state-of-the-art pollution control in 1898 is no longer acceptable. The societal goals which the engineer attempts to satisfy with a combination of technical feasibility and judgment have undergone drastic changes in the last 30 years (Harremoes 1997). Present day collection systems; many of which were designed and constructed in older periods when performance expectations and technical knowledge were less advanced than today, now must perform to today’s elevated standards. At the same time, sprawling urban growth has strained infrastructure in many areas, exacerbated by poor cradle-to-grave project management (Harremoes 1997). Designers of new collection systems must recognize and address the problems of past designs.

The current status of collection system infrastructure in the U.S. represents a combination of combined, sanitary and separate storm sewers. These collection systems vary in age from over 100 years old to brand new. While general design practices in the U.S. today are not drastically different than 30 years ago, current innovative research in Europe and Japan suggest that broad societal goals such as “sustainability” are not being achieved by current design practices in the U.S. Old combined sewers discharge raw sewage to receiving waters. I/I is a costly and wasteful problem associated with sewers. Sanitary sewer overflows (SSOs) discharge raw sewage from failed or under-designed separate systems. NPS pollution associated with urban areas is discharged from separate storm sewers. Proper transport of solids in sewers is still a misunderstood phenomenon, causing significant operational problems such as clogging, overflows, and surcharging.

This section provides an overview of the problems commonly associated with collection system infrastructure currently in use in the U.S. Designers of new collection systems must recognize these problems and address them with modern tools. Unsustainable design practices must not be allowed to be perpetuated in the field of urban water management. The useful life of the infrastructure is too long to simply design big systems to compensate for uncertainty. Following this section are sections describing innovative technologies being investigated and ways they might be used in the 21st century.

Combined Sewer Systems

CSS now constitute one of the remaining large-scale urban pollution sources in many older parts of major cities (Moffa 1990). In large urban areas, raw sewage, combined with stormwater runoff, regularly discharges to receiving waters during wet-weather. Water quality problems arise from NPS pollution in the stormwater portion of the discharge mixing with the sanitary wastes associated with the combined sewer. Low dissolved oxygen, high nutrient loads, fecal matter, pathogens, objectionable floatable material, toxins, and solids all are found in abundance in combined sewage (Moffa 1990). This mixture has led to some of the more difficult control problems in urban water management. However, CSS problems of today are the result of technology dating back to 1900 and earlier.

The traditional way to control CSO is to first maximize the efficiency of the existing collection system. This may include an aggressive sewer cleaning policy to maximize conveyance and storage properties of the system, reducing the rate of stormwater inflow, a re-evaluation of control points (frequently resulting in raised overflow weirs to maximize in-line storage in a static sense), and alterations of the wastewater treatment plant's operating policy to better accommodate short-term wet-weather flows (Gross et al. 1994). These measures were instituted as requirements for CSO discharge permits in 1994 by the EPA. The "Nine Minimum Control (NMC) Requirements" are (USEPA 1995b):

1. Proper operation and regular maintenance programs for the sewer system and CSO points.
2. Maximum use of the collection system for storage.
3. Review and modification of pretreatment programs to assure CSO impacts are minimized.
4. Maximization of flow to the WWTP.
5. Prohibition of dry-weather CSO discharges.
6. Control of solids and floatables.
7. Pollution prevention programs that focus on contaminant reduction activities.
8. Public notification to ensure that the public receives adequate notification of CSO occurrences and impacts.
9. Monitoring to effectively characterize CSO impacts and the efficacy of CSO controls.

In creating these permit requirements, the EPA has mandated that all owners must, at a minimum, adhere to these relatively low cost management activities.

These measures were frequently not enough, and less passive means of controlling CSO have been adopted in many cities. Storage of combined sewage, both in-line and off-line, has been used in a number of locations to capture frequent storms and the "first flush" of large events. As the capacity in the collection system and treatment works increases when the runoff subsides, the stored combined sewage is returned to the system for treatment (Field 1990). While not completely doing away with CSO (e.g., overflows occur when storage capacity is exceeded), storage of combined sewage has been a cost effective CSO control method (Walker et al. 1994).

Sewer separation has also been used in the U.S. This means of CSO control is expensive and is usually reserved for limited areas where severe overflow effects are concentrated in dense urban areas. As stated earlier, this means of control is not always adequate if polluted stormwater is discharged untreated. Traditional approaches of CSO mitigation including storage and separation are well documented in the literature and for detailed information the reader is referred to Moffa, 1990; USEPA, 1991a, 1993, 1995a, 1995b, 1995c, 1996a; WEF 1994a.

Other CSO control technologies that have been used on a more limited basis include high-rate treatment in the form of vortex or "swirl" separation technology (frequently in combination with storage), disinfection (including chlorination and ultra violet), micro screening, receiving water storage methods (including the flow-balance or the "Swedish method" developed by Karl Dunker), wetland treatment, floatable traps, and operation optimization techniques such as real time control (Field 1990; WEF 1994a; Seiker and Verworn (Ed.) 1996). Included in the category of CSO control technologies used on a limited basis is the previously mentioned on and below street storage of stormwater with the purpose of eliminating surcharging (Loucks and Morgan 1995, Walesh and Carr 1998).

An interesting development regarding CSSs is that due to contaminated stormwater runoff from urban areas that require treatment, combined systems are now at least being considered for new urban areas in some parts of Europe. CSS may in fact discharge less pollutant load to receiving water than separate systems where stormwater is discharged untreated and sanitary wastewater is treated fully. In southern Germany, CSSs are being designed with state-of-the-art BMPs to reduce the volume of stormwater entering the system. With reduced stormwater input, the number and volume of overflows are reduced over a traditional "old-fashioned" CSO, thus only discharging CSO during large, infrequent events, when the receiving water is most likely to be at high flow conditions also. This concept is discussed in more detail in subsequent sections of this chapter titled "Innovative Collection System Design – The State of the Art" and "Future Directions: Collection Systems of the 21st Century."

Inflow and Infiltration

Separate sanitary sewers serve a large portion of the sewered population in the U.S. These sewers are generally of smaller diameter than combined or storm sewers, and serve residential, commercial and industrial areas. While sanitary systems are not specifically designed to carry stormwater, per se, stormwater and groundwater do enter these systems. This is a common and complicated problem for sewer owners. So common, in fact, that the design of sanitary sewers must include I/I capacity, which may actually exceed pure sanitary flow rates (ASCE/WPCF 1982). The capacities of many collection systems are being exceeded well before the end of their design life, resulting in by-passes, overflows, surcharging and reduced treatment efficiency (Merril and Butler 1994).

Inflow

Inflow is defined as surface water entering the sewer via manholes, flooded sewer vents, leaky manholes, illicitly connected storm drains, basement drains (probably illicit in most areas) and by means other than groundwater. Inflow is usually the result of rain and/or snowmelt events.

Inflow, contrasted with infiltration, is generally easier to control by enforcement of regulations and through proper design of the sewer/surface water interface (ASCE/WPCF 1982). For example, in areas prone to nuisance flooding (such as development in riparian land), careful design of sewer vents and manholes can limit the amount of storm drainage entering the sanitary sewer. Water tight, elevated vents must be above a certain flood elevation, and solid manhole covers with half-depth pickholes will greatly reduce chances for surface waters leaking into the sewer (ASCE/WPCF 1982). Tests performed on manhole covers submerged in one inch of water indicate as much as 75 gpm leakage into the sewer depending on the number and size of holes through the cover (ASCE/WPCF 1982).

Enforcement of regulations restricting impervious areas from draining into the sewer will limit the amount of illicit stormwater entering the sewer (ASCE/WPCF 1982). A 1000 sq. ft. roof area may contribute nearly 11 gpm during a one inch/hour rain storm (ASCE/WPCF 1982). Foundation drains may also contribute drainage water that will quickly overload sanitary sewer systems. A careful examination of local conditions and regulations must be made before determining design inflow rates for a sanitary sewer. Frequently, regulations are difficult and expensive to enforce, and costly provisions may have to be made to eliminate illicit connections. As such, the costs of treating and pumping inflow must be weighed against the costs of enforcement and mitigative actions such as yard regrading, and expensive foundation drains. Every sanitary sewer will have some point at which the present value of mitigative actions is greater than the present value of future pumping and treatment costs. Inflow reduction beyond this point is not cost effective (ASCE/WPCF 1982).

Infiltration

Infiltration is defined as water that enters the sewer via groundwater. This usually occurs through leaky sewer pipe joints, manholes and service connections. Being a function of groundwater head above the sewer leak, infiltration can result from stormwater and/or snowmelt infiltrating into the ground and into the sewer. Thus a wet-weather event can trigger both inflow (usually a faster response to the system) and infiltration in the form of groundwater (ASCE/ WPCF 1982). During wet-weather, a fast increase in flow rate in the sewer is due to inflow and a delayed response during or following wet-weather is caused by storm-induced infiltration. This wet-weather-dependent I/I in a separate sanitary sewer may behave nearly as fast as a CSS and, in turn, trigger SSOs (Miles et al. 1996). Infiltration can also occur purely as a function of groundwater elevation, independent of wet-weather. During dry weather the night-time minimum flows found in the sewer are from pure infiltration. Infiltration is usually much more difficult and costly to control than inflow. A typical sanitary sewer with likely sources of I/I indicated is shown in Figure 6-1.

Current design standards usually require that a certain amount of infiltration be accounted for in the design of a gravity sanitary sewer. Infiltration rates are given in units of volume per time per mile of pipe, normalized by the diameter of the pipe. In the U.S., values are reported in units of gpd/inch diameter/mile (gpd/idm). The joint ASCE-WEF design guidance for gravity sewers gives general guidelines for the volume of infiltration that should be used in capacity calculations for the a sewer at the end of its design life. Variations of local guidelines in the U.S. are presented in Table 6-1.

Table 6-1. Variations of infiltration allowances among cities (ASCE/WPCF 1982).

Cities Reporting		Allowance (gpd/idm)
Number	%	
4	3.1	1500
4	3.1	1000
1	0.8	800
2	1.6	700
1	0.8	600
63	49.2	500
11	8.6	450 to 300
16	12.5	250 to 150
21	16.4	100
5	3.9	50
Total = 128	Total = 100.0	Weighted Average = 422

Note: gpd/idm x 0.000925 = m^3/day/cm diam/km

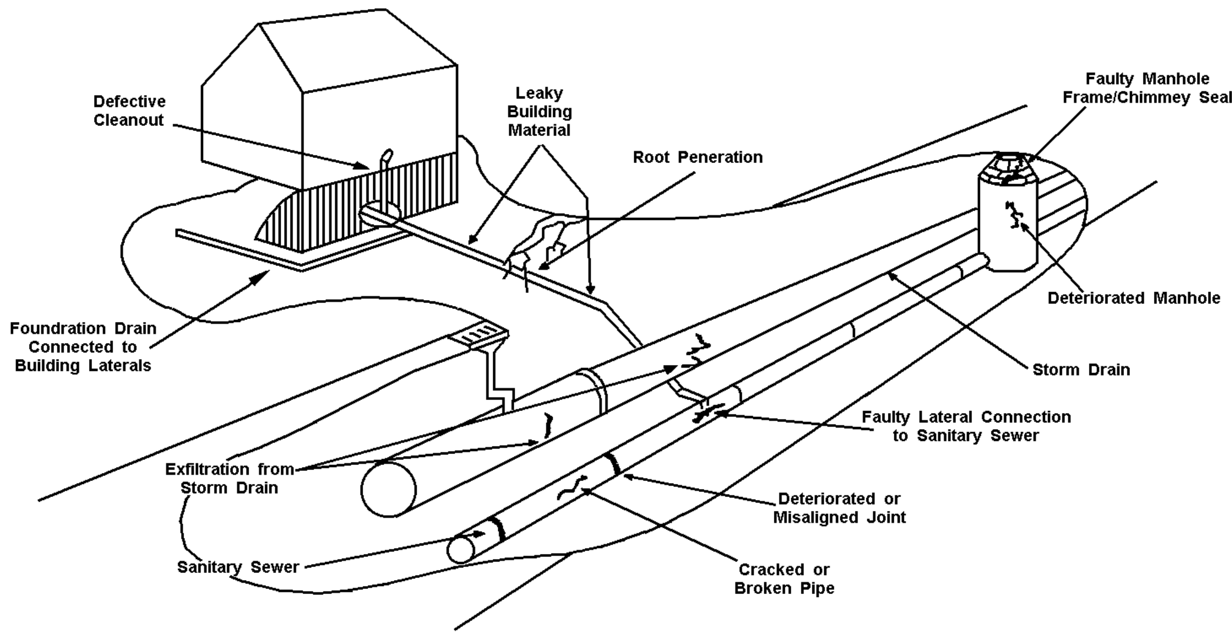

Figure 6-1. Typical entry points of inflow and infiltration (USEPA 1991a).

Inflow/Infiltration Analysis and Design Challenges

In existing sewers, the relative amount of I/I may be dramatic. Relative I/I contributions on an annual and monthly scale, respectively, are shown in Figures 6-2 and 6-3. The effect of groundwater elevation is evident in the annual analysis shown in Figure 6-2, where infiltration increases with groundwater. Inflow, on the other hand, tends to be a function of rainfall intensity, as seen in Figure 6-3.

A comparison was made of typical wastewater inputs versus the infiltration rates shown in Table 6-1 for an eight inch sanitary sewer. Typical wastewater flows were calculated for three population densities using 60 gpcd (DeOreo et al. 1996). Lateral spacing was assumed to be 50 ft. (high density), 100 ft. (medium density), and 150 ft. (low density). Each lateral was assumed to receive waste flows from four persons, thereby discharging 240 gpd. The results are shown in Figure 6-4. The conclusion from this theoretical comparison based on reasonable values is that typical infiltration rates allowed in the U.S. are a significant portion of the total wastewater flow.

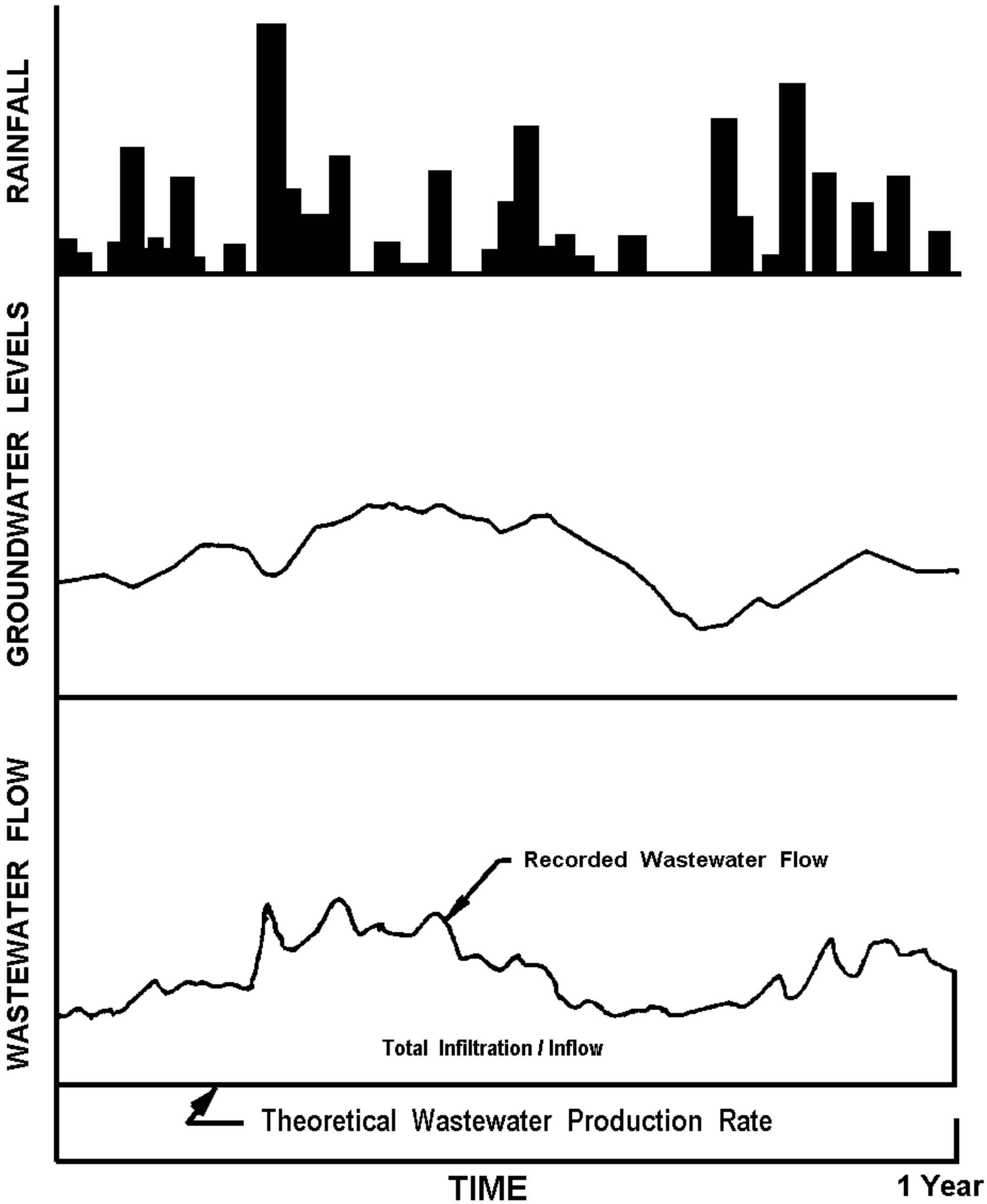

Figure 6-2. Annual contribution of I/I (USEPA 1991).

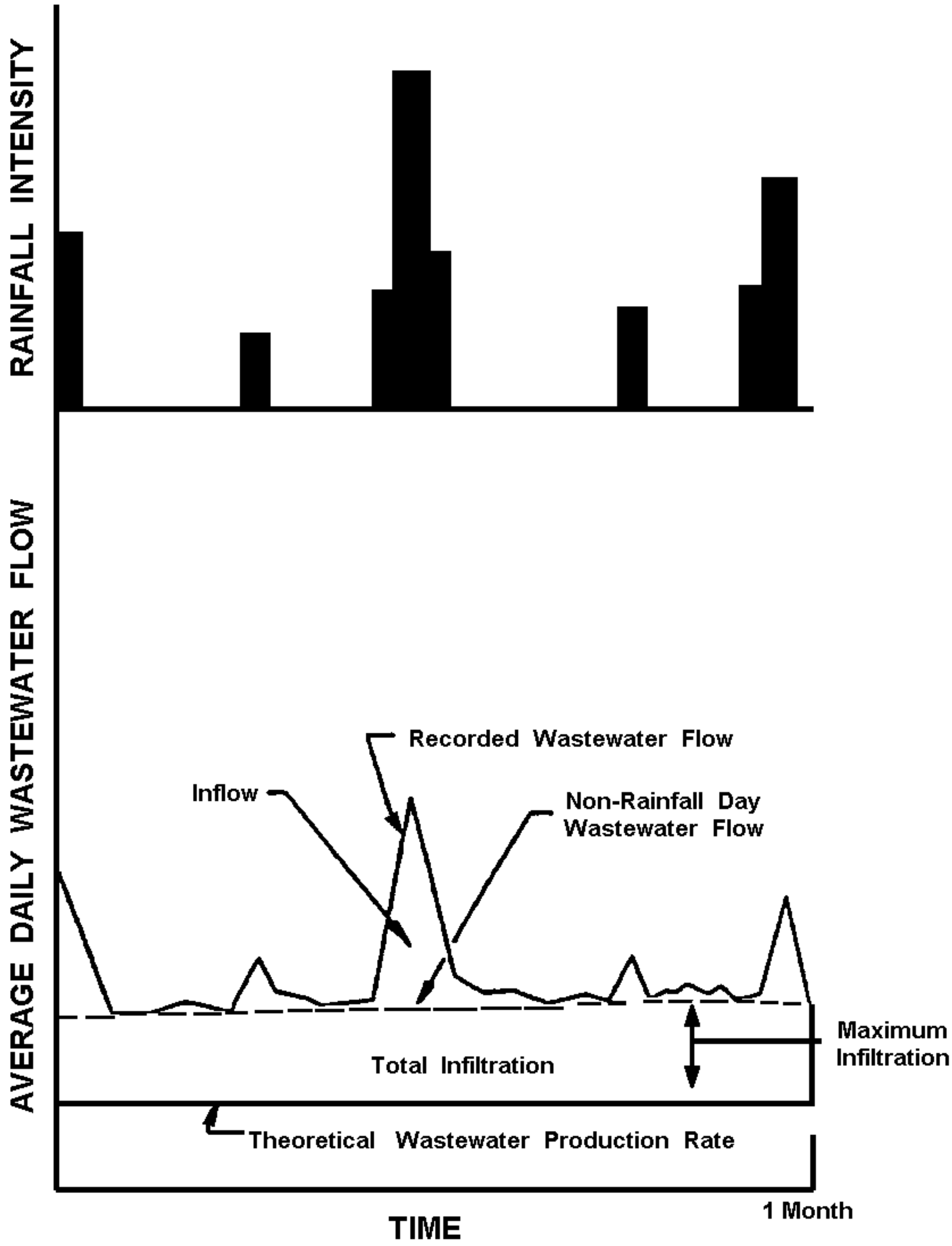

Figure 6-3. Monthly contribution of I/I (USEPA 1991a).

From Table 6-1, 50% of U.S. cities allow 500 gpd/idm or more. Table 6-2 shows the per capita I/I contribution for the three population densities for 500 gpd/idm. The results emphasize that infiltration is a significant portion of the wastestream, even using "moderate" rates such as 500 gpd/idm for an eight inch pipe.

Another comparison was made by using design values based on tributary area. Pre-1960s sewers were designed for 2,000 to 4,000 gal/acre/day I/I. Current design practice is 1,000 gal/acre/day. By comparison, per capita waste flow before 1960 was assumed to be 200 to 400 gal/capita/day, and the modern design value is 100 gal/capita/day (Heaney et al. 1997). The conclusion is that collection systems are designed for two to 10 times the dry-weather flow (Heaney et al. 1997). Therefore most of the sewer capacity presently "in the ground" is there to accommodate I/I (Heaney et al. 1997).

Table 6-2. Comparison of average daily wastewater and infiltration for one mile of 8 inch sanitary sewer based on 500 gpd/idm.

Population Density	Lateral Spacing (ft)	Population (four persons per lateral)	Per Capita Waste-water (gpd)	Total Waste-water (gpd)	Infil. (gpd)	Total (gpd)	Infil. (%)	Per Capita Infil. (gpd)
Low	150	141	60	8,460	4,000	12,460	32%	28
Medium	100	211	60	12,660	4,000	16,660	24%	19
High	50	422	60	25,320	4,000	29,320	14%	9.5

A review of 10 case studies in USEPA (1990) indicates that peak waste flows ranged from 3.5 to 20 times the average dry-weather flow (DWF). System surcharges would typically occur as the ratio reached 1:4 or 1:5 (USEPA 1990). Petroff (1996) estimated that I/I accounts for almost one half of the average flows to WWTPs in the United States. Houston, TX, measures peaking factors of 1:30 with maximum ratios reaching 1:50 (Jeng et al. 1996).

An example of the problems associated with reporting extraneous flows is found in a survey of 102 municipal wastewater management agencies from across the U.S. The survey was conducted by the Association of Metropolitan Sewerage Agencies (AMSA) and reported in AMSA (1996). The distribution of per capita wastewater flows and I/I from this survey is shown in Figure 6-5. The average per capita wastewater flow is 87.4 gpcd and average annual I/I is 37.4 gpcd (AMSA 1996).

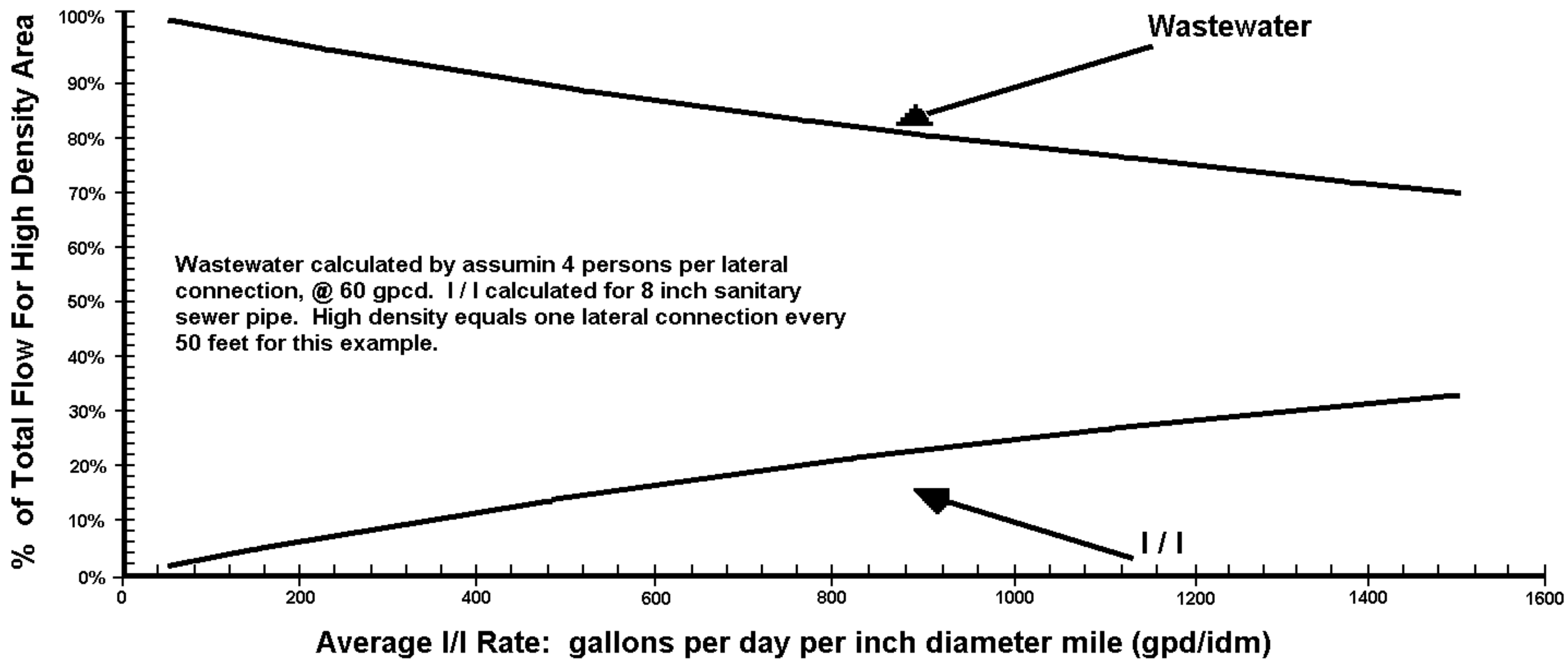

Figure 6-4a. Comparison of infiltration flow rates and residential flow rates for a one mile long, eight inch sanitary sewer (high population density).

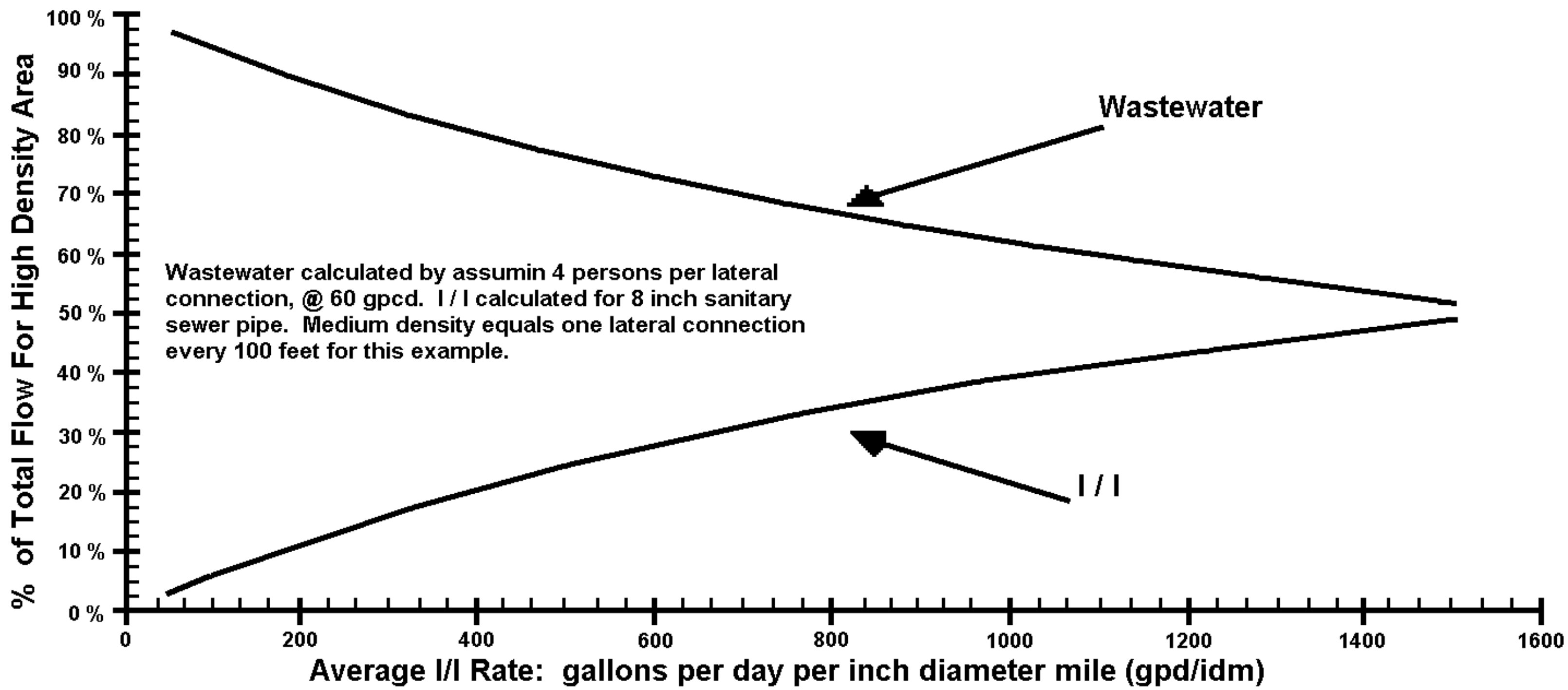

Figure 6-4b. Comparison of infiltration flow rates and residential flow rates for a one mile long, eight inch sanitary sewer (medium population density).

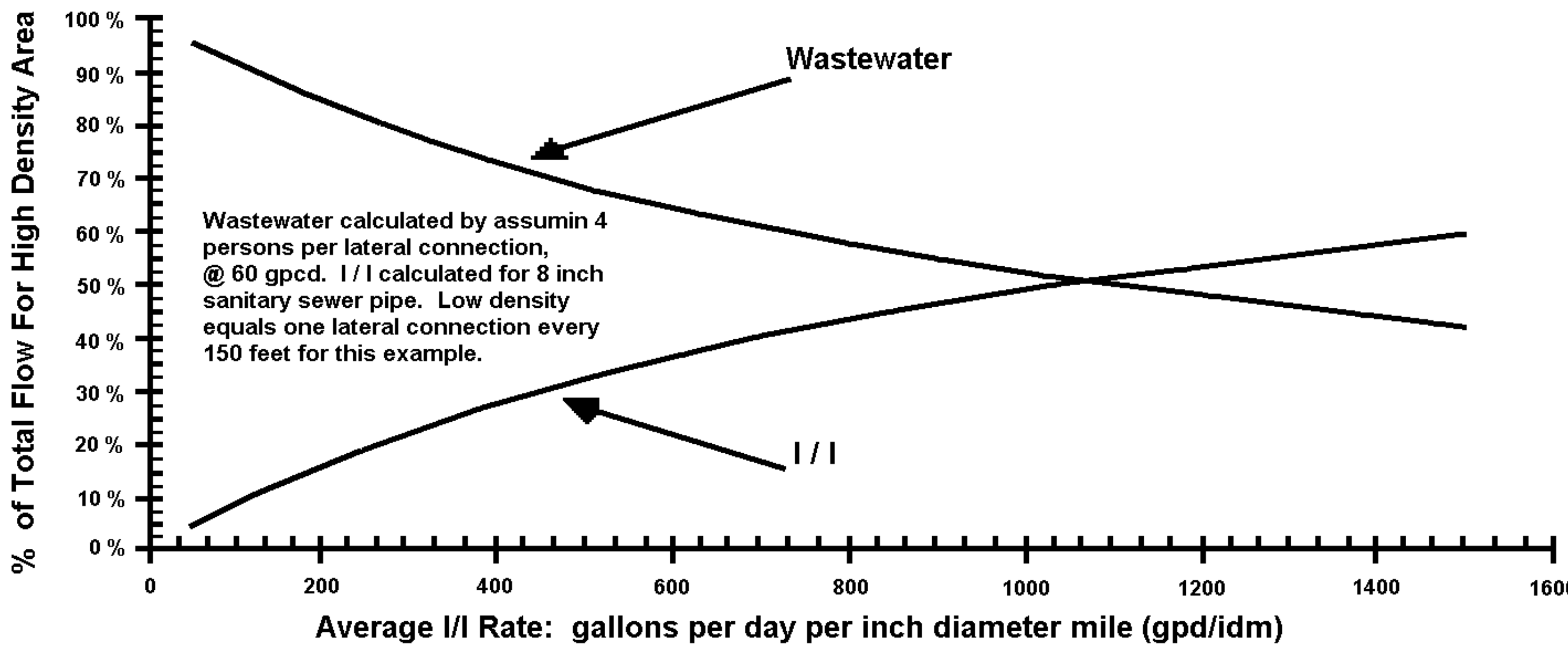

Figure 6-4c. Comparison of infiltration flow rates and residential flow rates for a one mile long, eight inch sanitary sewer (low population density).

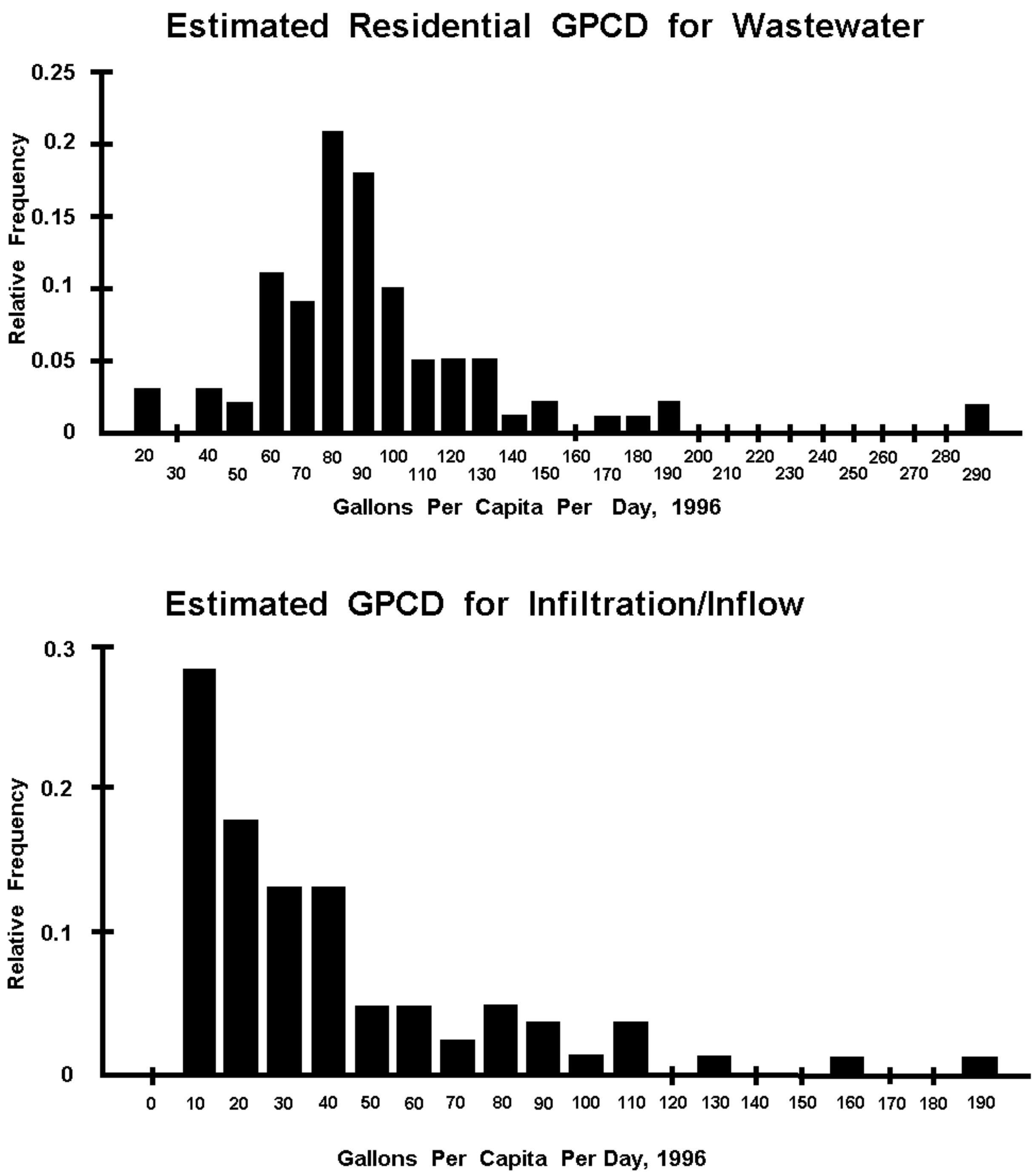

Figure 6-5. Histogram of average annual residential wastewater and I/I rates on a per capita basis from 102 U.S. cities (AMSA 1996).

Actual residential wastewater use, however, was found by DeOreo et al. (1996) to be 60 gpcd with little variance. Also, the I/I flow values reported in the AMSA survey are lower than reported I/I values on a national basis reported from other sources (e.g., Petroff 1996). It is likely that I/I values are under-reported in the AMSA survey, the difference being in inflated residential rates. For instance, the difference of reported residential and actual wastewater is 27.4 gpcd (87.4 - 60 gpcd). Added to the average reported I/I value, 37.4 gpcd, the result is an average annual I/I flow of 64.8 gpcd from across the nation. This value is in closer agreement with other sources, and highlights the fact that I/I can be a nebulous, imprecise quantity to estimate.

Methods of I/I detection are usually part of a complete Sewer System Evaluation Survey (SSES), which may include flow monitoring, pipe and manhole inspection, smoke testing, dye trace testing, and remote video surveys to isolate areas of high I/I (Rudolph 1995). These methods provide data that help locate areas with deteriorated sewers. Further analysis will identify areas contributing the most volume per sewer length and, therefore, the most likely areas for rehabilitation. Various methods are available for rehabilitation, including sewer lining, sealing, and reconstruction. Traditional approaches to I/I rehabilitation may be found in USEPA (1991a), ASCE/WPCF (1982), WEF/ASCE (1994), Read and Vickridge (Ed.) (1997).

Fixing an I/I problem can be an expensive rehabilitation project. It is only cost effective when the present value of the future costs of pumping and treating the I/I exceed the rehabilitation costs over the design life of the sewer including rehabilitation (WPCF 1982). Some older sanitary sewers may in fact have been designed to accept infiltration in order to dewater areas that may suffer damages from a high groundwater table. Other failing sewers may be providing the same function, though not originally designed to function this way. The added costs of damages resulting from high groundwater tables must be accounted for in an I/I evaluation. I/I rehabilitation policy must address this potential problem, as residents are likely to blame the I/I rehabilitation as “causing” groundwater flooding if they have been accustomed to this benefit for some time.

One problem associated with estimating and measuring I/I in existing sewers is the lumping or combining of inflow and infiltration. While both are sources of extraneous flow, they originate from different sources, tend to impact the system on greatly different time scales, and have different remedial measures. A likely reason that inflow and infiltration are combined together is the typical downstream “lumped” flow measurement at the WWTP headworks. For cost purposes, because inflow and infiltration are both extraneous to the waste stream, I/I are treated together.

This combining has led to confusion in reporting measured values in terms of average or peak flows for design or costing calculations. For pumping and treatment costs, average annual volumes are used for power and equipment cost estimation. In this case, reporting I/I together is correct. For other purposes, flow rates are important. Lack of frequency and duration of peak flows has exacerbated the uncertainty associated with extraneous flows. For example, the values in Table 6-1 were taken directly from a modern design guidance. While the figures in Table 6-1 only represent infiltration, there is little or no discussion as to whether these flows are an average flow over a year, a season, or day. If these are taken to be design allowances for additions to existing sewers, what is the return period of the rates given? This has design ramifications for the expected performance of the system at the end of its design life and the frequency of failure (e.g., surcharging and overflows).

Estimation of flow for wastewater design purposes has historically been more of an art than a science. While recent research has shown little variability in residential wastewater flows (DeOreo et al. 1996), designers have had to estimate peak and average I/I flows such as presented in Table 6-1 and 6-2 and in Figures 6-2 and 6-3. For new sewer design, inflow into the system can be expected to be insignificant if a surface drainage system is designed properly and if illicit connections are reduced by enforcement of local regulations (ASCE/WPCF 1982, Tchobanoglous 1981).

Expected infiltration rates at the end of the project life are uncertain and, therefore, must be estimated by the designing engineer. The uncertainty is due to site specitivity of soil and groundwater conditions and uncertainty of the expected future performance of modern construction techniques. For estimating peak infiltration rates, old systems range from 10 m^3/ha-d for 5,000 ha service area to 48 m^3/ha-d for 10 ha service area, and new systems range from 3 m^3/ha-d for 5,000 ha service area to 14 m^3/ha-d for 40 ha service area (Tchobanoglous 1981). The assumption is that performance has increased due to improved construction. While this is very likely true, to truly estimate life cycle costs the designer needs additional information on the frequency and duration of infiltration rates. The absence of a definition for “peak” in terms of time period (e.g., hour, day, season) and frequency (e.g., equaled or exceeded once every ten years) is very important for estimating performance. This information can only come from long-term, continuous measurement. Likewise, “average” infiltration rates for new sewers, without a definition of the return period or the duration of the average range from 2 m^3/ha-d for 5,000 ha service area to 9 m^3/ha-d for 40 ha service area (Tchobanoglous 1981). In the future, after a period of time when actual extraneous flows have been continuously measured for a variety of systems and in a variety of areas, flow/duration information will be available to reduce the uncertainty in extraneous flow estimation. Until that time, collection systems owners will continue to operate under a large cloud of uncertainty.

Reducing the amount of I/I in new sewers for the entire life of the collection system to near zero is imperative. This is critical from a variety of viewpoints. From a pure cost standpoint, the costs of treating I/I over a long period of time are large. From a design standpoint, the expected I/I from current systems near the end of their useful life may exceed sanitary flow and “drive” the design. In other words, if I/I can not be reduced to near zero, the designer must increase sewer design capacity to account for it. The sewer owner pays for a larger system than is required by societal demand, and then must pay to treat the I/I over the entire project life. Clearly this is not cost efficient or sustainable if the system can be constructed and designed from the outset as "tight". Generally, the added costs of I/I-proofing the sewer will be far less during original construction than being forced to pay for expensive rehabilitation projects well into the lifespan of the system. As an integral part of overall urban water management, I/I control for new collection systems should be considered a major design objective.

In most cases, excessive I/I can be traced to poor construction techniques and materials and/or poor enforcement of policies regarding illicit connections. Current bidding practice is designed to minimize initial costs on the part of municipalities. However, the goal should be to minimize life-cycle costs given a certain level of performance over the entire project life. For the sewer owner of the 21st century (who may not be a public entity), measures must be taken to ensure that the construction and design contractors have a vested interest in the acceptable long-term performance of the collection system.

Sanitary Sewer Overflows

When the capacity of a sanitary sewer is exceeded, untreated sewage may discharge to the environment. SSO may be due to excessive I/I, from an under-designed (or over-developed) area releasing more sanitary flow than the system was designed for, from a sewer blockage, or from a malfunctioning pump station. The distribution of SSO causes from a sample of six communities is shown in Figure 6-6. An SSO can occur at the downstream end of a gravity sewer near the headworks of a WWTP or at relief points upstream in the system. These relief points may have been designed into the system, or retrofitted to alleviate a problem, or unexpected surcharging through manholes, basements or sewer vents. SSO causes from two case studies, in Fayetteville, AR, and Miami, FL., are shown in Tables 6-3 and 6-4. These data show that I/I is a significant cause of SSO, again reinforcing the importance of the need for data measurement discussed in the previous section.

SSOs are undesirable under any circumstance because they result in relatively high concentrations of raw sewage flowing directly to surface waters. Wet-weather SSOs may behave in a fashion similar to CSOs in extreme cases, though rehabilitation of the system is different. Instead of treating overflow (as is often the case of CSOs where the CSS provides primary drainage), wet-weather SSOs are more typically treated by attempting to remove wet-weather sources or removing hydraulic-capacity bottlenecks. Dry-weather SSOs are especially unwanted because the receiving water may not be running as high as during wet-weather, thus triggering more severe water quality degradation. Heaney et al. (1997) address a more detailed discussion of the relationship between wet-weather triggered overflows and receiving water assimilative capacity.

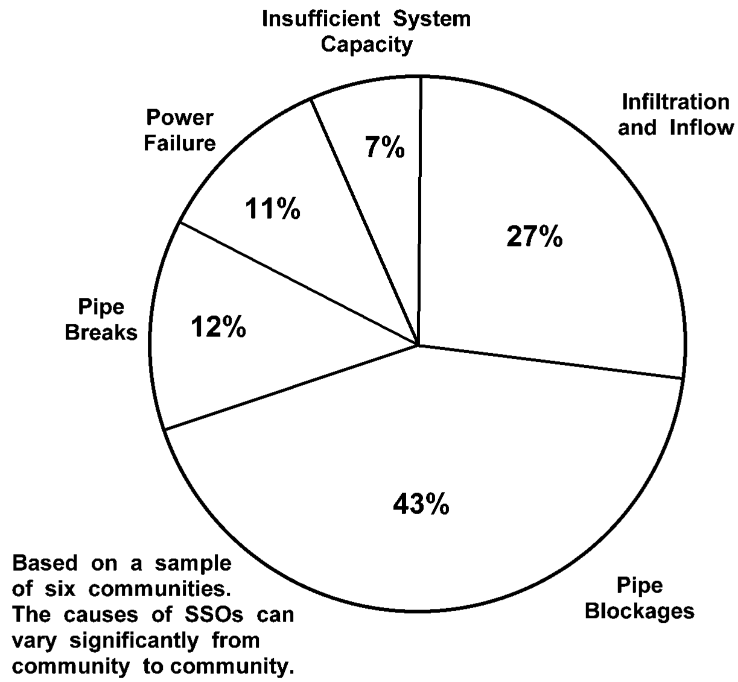

Figure 6-6. Estimated occurrence of SSO by cause (USEPA 1996b).

Table 6-3. Causes of SSOs in Fayetteville, AR (Jurgens and Kelso 1996).

Cause of SSO	1991 (%)	1992 (%)
I/I	39	36
Roots	19	24
Grease	25	13
Roots/grease	6	7
Other	11	20
Total (%)	100	100
Number of SSOs	161	123

Table 6-4. Causes of SSOs in Miami, FL (Clemente and Cardozo 1996).

Cause of SSO	Percent of Total
Pipe breaks (deterioration and accidental)	36
Pump station failures	30
Insufficient capacity due to wet-weather	19
Pipe blockages	15
Total	100

For new collection systems, the reasons for SSOs need to be thoroughly understood. Relief points for excessive flow during wet-weather events in sanitary sewers should not be a design concern if I/I is truly minimized. Likewise, if land use management plans are properly coordinated with system design and operation, then sewer capacity should not cause SSOs. However, surcharging due to clogging may occur even under the most rigorous of maintenance programs. Therefore, a pipe failure analysis should be conducted in the design phase to understand the reliability of the system. Relief points near the headworks of the WWTP should also be part of the design, to protect the treatment plant from possible excessive flows from unexpected sources. For example, a failure scenario could include a water main break that floods the sewer, or extreme surface water flooding that enters via non-illicit means, such as external sewer. In general, an integrated urban water management program of the future will have a minimum of SSOs, but collection system owners and regulators should at some point in the project life expect that some form of discharge due to surcharging will occur.

Separate Stormwater Collection Systems and Non-Point Sources

Separate storm sewers of one form or another can be found in virtually every municipality in the U.S. They are typically designed to collect stormwater from urban/suburban areas to prevent nuisance flooding (e.g., usually storms with return frequencies less than 10 years). This "level of protection" from flooding replaces an economic efficiency analysis that would ideally be performed on the basis of the worth of the potential damages resultant from flooding (ASCE/WEF 1993). The selection of return period is related to the exceedance probability of the design storm and not the reliability (or probability of failure) of the drainage system (ASCE/WEF 1993). Typical different levels of protection depending on the land use of the service area are presented in Table 6-5.

Table 6-5. Typical design storm frequencies (ASCE 1993).

Land Use	Design Storm Return Period (years)
Minor Drainage Systems	
Residential	2-5
High value commercial	2-10
Airports (terminals, roads, aprons)	2-10
High value downtown business areas	5-10
Major Drainage System Elements	< 100

A more thorough analysis of the expected performance of a drainage system would include a continuous mathematical simulation of the response of the system over an extended period of time using measured rainfall in the service area. This analysis would provide a more accurate estimation of the expected return period at which the capacity of the drainage system would be exceeded and the magnitude of the exceedances. This information may be used in conjunction with property values to estimate the distribution of expected damages that result from system exceedance thus providing a more rational basis of design (USACE 1994). In addition, the quality of the discharged stormwater may be mathematically simulated, which would provide information that could be used for receiving water management decisions. A detailed account of the benefits of continuous storm drainage accounting is provided in Heaney and Wright (1997).

Typical elements of a stormwater system include curbs, gutters, catchbasins, subsurface conveyance to a receiving water, sometimes first passing through a passive treatment facility such as a dry detention pond, a wet pond, and/or through a constructed wetland (ASCE/WEF 1993). This typical system may have open channels or swales instead of catchbasins and pipes.

Separate storm sewers may transport various forms of diffuse or NPS pollution to the receiving water. The amount and type of contaminant transported is heavily dependent on the land use of the tributary area, the rainfall/snowmelt characteristics of the area, and the type of storm sewer. Recent studies have shown a relationship between the impervious tributary area and receiving water quality. While the volume and time to peak of storm hydrographs have long been known to be adversely impacted by imperviousness, the water quality degradation aspects of imperviousness are still not completely understood.

Solids and Their Effect on Sewer Design and Operation

The fundamentals of modern sewer design haven't changed in many respects since the beginning of the century. Review of "Design of Sewers" by Metcalf and Eddy (1914), indicates that the fundamentals of minimum and maximum velocities, grade, flow rate prediction, and solids transport were in place at the turn of the century after hundreds of years of trial and error designs dating back to ancient civilizations. Modern design has significantly refined the information used in design, but the basic engineering criteria have remained, much to the credit of early sanitary engineers.

The purpose of sewer collection systems has always been to safely transport unwanted water and solids. Historically, sewer design has focused primarily on the volume and flow rate of the fluid, and has assumed solids will be carried with the fluid if certain "rules-of-thumb" regarding velocity are followed. This imprecise method of designing for solids transport has been a costly and significant source of maintenance needs over the years in the U.S. and elsewhere.

Recent research conducted in Europe (Ashley (Ed.) 1996) has focused on the age-old question of transport of solids in sewers. The flow rate, velocity and size of pipe are all important in determining the amount and size distribution of solids a particular sewer will carry. Therefore, along with flow rate, the solids transport question is one of the most fundamental questions that must be addressed when calculating costs. It is a vexing question, because solids transport is a function of flow rate, velocity, pipe size, pipe material, gradient, solids concentration, size distribution of the solids, and type of solid (e.g., colloidal or non-colloidal, and grit). Also important is the question of solids transformation in the collection system. Fundamental research conducted in Europe has shed some light on this issue (Ashley (Ed.) 1996, Sieker and Verworn (Ed.) 1996, Ackers et al. 1996).

A historic reference to a minimum design velocity is found in Metcalf and Eddy (1914), where an early sewer design in London is cited as using a value of 2.2 fps to avoid unwanted deposition in sewers. Other early work on minimum grades for various pipe sizes was done by Col. Julius W. Adams in designing the Brooklyn sewers in 1857-59 (Metcalf and Eddy 1914). Col. Adams' recommended sewer grades are shown in Table 6-6, and compared with modern values found in Gravity Sanitary Sewer Design and Construction (ASCE/WPCF 1982). These early designers recognized that the minimum mean velocity to avoid deposition was dependent on the pipe diameter.

However, in the 1994 WEFTEC proceeding "Collection Systems: Residuals and Biosolids Management", a paper entitled "Two feet per second ain't even close" by P. L. Schafer discusses the problems associated with deposition in large diameter sewers due to using a "rule-of-thumb" design value of two fps (Schafer 1994). Modern design guidelines still state: "Accepted standards dictate that the minimum design velocity should not be less than 0.60 m/sec (2 fps) or generally greater than 3.5 m/sec (10 fps) at peak flow." (ASCE/WPCF 1982). One problem with this recommendation is the lack of peak flow definition. Should this be the seasonal, monthly, daily, or hourly peak flow? The frequency and duration of the flushing flow are critical to the proper performance of the sewer. Ideally, a settled sewer particle at the furthest end of the collection system will be re-entrained into the waste stream and carried to the WWTP. Clearly the minimum velocity design problem has not been resolved.

Sewers that exhibit sediment deposition are prone to a multitude of problems over time. Excess sedimentation promotes clogging, backwater and surcharging and may promote corrosion by producing hydrogen sulfide (Schafer 1994). Because sedimentation problems are more likely to occur in larger diameter sewers, such as trunk sewers, the associated costs of sewer failure may be substantially greater than in a smaller diameter pipe. In combined systems, the in-line storage that is taken up in a heavily sediment-laden trunk or interceptor sewer will tend to increase the volume and frequency of overflow events (Mark et al. 1996). In addition, the deposited sediments in combined systems represent a build up of pollutants. that may resuspend during wet-weather (Gent et al. 1996).

Table 6-6. Comparison of recommended minimum sewer grades and velocities over the years.

Source	Type of sewer and pipe diameter	Minimum Slope (ft/ft)	Minimum Velocity (fps)
Balzalgette, London, c. 1852 (1)	Large intercepting sewers – combined system		2.2
Roe, London, c. 1840 (1)	Large intercepting sewers – combined system	0.002	
New Jersey Board of Health, 1913 (1)	8” – Sanitary sewer (n = 0.013)	0.004	
“	12” – Sanitary Sewer (n = 0.013)	0.0022	
“	24” – Sanitary Sewer (n = 0.013)	0.0008	
Metcalf and Eddy, 1914 (2)	Combined systems		2.5
“	Sanitary systems		2.0
WPCF/WEF 1982 (3)	Sanitary systems		2.0
WEF/ASCE 1992 (4)	Storm sewers		2 - 3
Acker et al. 1996 (5)	150 mm (5.9 in)	0.0062	2.2
“	225 mm (8.85 in)	0.0043	2.36
“	300 mm (11.8 in)	0.0032	2.46
“	450 mm (17.7 in)	0.0024	2.59
“	600 mm (23.6 in)	0.0021	2.95
“	750 mm (29.5 in)	0.0022	3.48
“	1000 mm (39.3 in)	0.0025	4.43
“	1800 mm (70.8 in)	0.0028	6.66

Note:
1. Col. Julius W. Adams (c. 1859) in Metcalf and Eddy (1914)
2. Metcalf and Eddy (1914)
3. ASCE/WPCF (1982)
4. ASCE/WEF (1992)
5. Ackers et al. (1996)

The movement of solid material in flowing water is a complex phenomenon that depends on the nature of the solid particles, the nature of the flow, and the nonlinear interaction between the two. A solid particle undergoes acceleration from the force of gravity, from the average advective motion of the water, and from the local turbulent motions of the water. Particles may be suspended in the water column of the sewer, deposited along the bed of the sewer, or slowly move along the bedload of the sewer. Once deposited under low flow conditions, a particle may resuspend into the water column under high flow conditions. In addition, a particle may exhibit cohesive properties, adjoining with other particles both in suspension or in the bed after deposition. Sewer particles may be organic, with low specific gravity and break down both physically and biologically while in the sewer.

When considering sewer collection systems, the proper transport of solids is crucial to a correctly functioning system. There are distinct areas where deposition should be avoided, (e.g., the conduit network) and also areas where deposition is desired, (e.g., treatment works). The system should function under a wide range of hydraulic conditions and under a wide range of solid loadings. The solids may also vary widely in character, which may alter the performance of the sewer.

To avoid deposition, a common design method is to calculate the shear stress required to move the largest size of particle expected in the sewer under average or high flow conditions (Schafer 1994). This assumes that the frequency of the high flow is enough to avoid excessive deposition and the subsequent creation of a permanent bed layer. The critical shear stress of a particle is defined as the minimum boundary stress required to initiate motion (Schafer 1994). Chow (1959) indicates that shear stress is a function of the specific weight of water and the hydraulic radius and invert slope of the sewer. Various values of critical shear stress have been recommended, depending on the maximum size of particle found in the sewer. Values of critical shear stress recommended by various researchers are shown in Table 6-7.

Table 6-7. Recommended critical shear stress to move sewer deposits (Schafer 1994).

Recommended critical shear stress		Reference	Conditions
N/m^2	lb/ft^2		
4	0.08	Lynse 1969	Sanitary sewers
4	0.08	Paintal 1972	Sanitary sewers
1.5 to 2.0	0.03 to 0.04	Schultz 1960	German work
1 to 2	0.02 to 0.04	Yao 1974	Sanitary sewers with small grit size
3 to 4	0.06 to 0.08	Yao	Storm sewers
2.5	0.05	Nalluri 1992	Sand with weak cohesiveness
6 to 7	0.12 to 0.14	Nalluri 1992	Sand with high cohesiveness

Note: 1 N/m^2 equals 0.02064 lb/ft^2

Schafer (1994) recommends that the lower end of the shear stress range in Table 6-7 is adequate only for waste streams with small particle size and limited grit, and when flushing flows may be expected daily. The high end of the range is appropriate when the waste stream contains heavy grit and gravel, as is common in combined or storm sewers (Schafer 1994). Table 6-7 indicates that commonly used design values for the minimum flushing velocities in sewers are not adequate to scour grit from large sewers. Consider, for example, a 48 inch diameter sewer transporting a reasonable load of grit. Minimum velocities in the range of 4.0 fps are required to flush deposited grit, far greater than the 2.0 fps recommended in some design guidelines. However, European research shows that bed stress is the most important criterion, and a minimum bed shear stress of $2N/m^2$ is required to ensure sediment transport (Ashley and Verbanck, 1997).

Uncertainty in key design parameters is the source of unnecessary cost. If under-designed, operation and maintenance costs are likely to be high. If over-designed, additional unnecessary capital costs are incurred as are high maintenance costs due to solids deposition at low flows. Just as this was shown to be true in the discussion of I/I, so it is also true for designing sewers for solids transport.

However, in addition to the lack of high quality frequency/duration information regarding flows, the designer concerned with solids transportation must also contend with a physical process about which only the rudimentary nature is known. The relationship between the solids concentration, the distribution of settling velocities, and the dynamics of movement are not well understood for gravity pipe flow. Operational costs will be incurred if the frequency and duration of velocities are not enough to regularly cleanse the pipes. Deposition in uncleaned sewers will cause SSOs. Thus environmental costs are also incurred. If over-designed, the sewers will remain clean, however additional excavation and material costs will be incurred.

While attempts have been made to estimate costs of I/I and SSOs on a national basis, there are no cost estimations of improperly designed sewers. It is likely that these costs, if known, would dwarf those for I/I and SSOs. As is the case with I/I estimation, new systems that record and store operational data will be invaluable to improving design techniques for solids transport.

Predicting Pollutant Transport in Collection Systems

A problem associated with present day collection systems is that, given the current state of computer simulation technology and knowledge, simulating pollutant transport correctly through a complex collection system is very difficult. This is especially true if complex hydrodynamics and continuous simulation are required. Due to the complex nature of the governing hydrodynamic equations, coupled with sediment transport equations, continuous simulation of the response of a collection system is nearly impossible for realistic system configurations. However, the designer of new collection system should realize that this will likely not be true in the near future. Data retrieval via Supervisory Control And Data Acquisition (SCADA) systems should be considered a major system component in collection systems of the 21st century. Data acquisition will be imperative for real time control and advanced simulation/optimization and designers of new collection systems must recognize that the technology available at the end of the project life of the collection system will be far advanced from what is available today.

To properly simulate pollutant discharges from a sewer system, a model must have the ability to simulate the movement of solids in sewers (Gent et al. 1996). Research conducted in the UK has shown four types of sewer transport (Gent et al. 1996):

1. Suspended transport (occurs at or slightly slower than the flow rate).
2. A dissolved or very fine rate (occurs at the ambient flow rate).
3. A dense near-bed layer (occurs during periods of low flow).
4. A course bed load layer (occurs during periods of high flow or in steep sewers).

The near bed and bed layer are the primary pollutant transport mechanisms and are also the main sources of deposition (Gent et al. 1996). Current trends in mechanistic modeling of collection systems indicate that these transport mechanisms will be part of future mathematical models. It should be assumed that future collection systems will have extensive data collection systems and that computational capabilities will be advanced to the point of accurately simulating pollutant behavior in a pipe network.

Characteristics and Treatability of Solids in Collection Systems

When considering the transport and/or treatment of solids in sewers, the cumulative effect of gravity on the overall particle distribution must be measured. Sewer solids may occur in a wide range of specific gravities and an equally wide range of shapes. The settling characteristics of the entire distribution of solids must be known to properly establish solids behavior in pipes, pumping stations and treatment works. Due to the site specific nature of solids, local data on settling velocities are greatly preferred over literature values.

Several forms of measurement tests have been developed and Pisano (1996) provides a summary of the currently accepted techniques. All methods provide estimates of the distribution of settling velocities for a particular solids sample. However, the results are a function of the protocol used and, therefore, not absolute. Pisano (1996) shows an example plot of settling characteristics for various forms of sewer samples. Data show a wide range of "treatability," that is, ability to settle as determined in laboratory tests. When considering design of new systems that include wet-weather treatment, a standardized measure of settling velocity distribution data will be needed.

Innovative Collection System Design - The State of the Art

Recent work in all aspects of sewer collection systems, from design and facilities-planning level research to construction and operation and maintenance, shows promise for greatly improved collection system performance for the next century. In addition, drastically new technologies are being considered which may greatly affect the future configuration of urban water management. Some innovators in the field are advancing ideas to replace water-intensive waste removal systems.

This section provides an overview of many aspects of sewer concepts. It is generally organized in terms of increasing innovation. In other words, the first examples remain closest to present day systems and the last innovations described deviate furthest from current design concepts. The reader is reminded that this section is an overview of innovative ideas in the field of waste management. Many of these ideas are only now being tested and inclusion in this guidance should not be misunderstood as a recommendation by the authors or the USEPA. References are provided for the interested reader to follow up on performance testing in the future. The section following this one attempts to provide these technologies in a future scenario-type context.

During the past decade, many changes in the understanding of global and local effects of urbanization, population growth, and land use have brought about a concern for future generations. This concern is manifested in a concept for future development called "sustainability" which is discussed in Chapter 3 of this report. While there are many interpretations of the concept of, engineers have attempted to bring the fundamental concepts to the practitioners and policy makers. In the field of urban water management, sustainability concepts are being used to critique current water management practices, and bring fresh ideas of waste management to decision makers. Henze et al. (Ed.) (1997) provide the most recent work in this area. Innovative collection system concepts attempt to reconcile problems discussed in the earlier section of this chapter titled "Problems Commonly Associated with Present Day Collection Systems." While rethinking the whole concept of transporting urban wastes via underground water-driven sewers.

Recent literature in the area of sewer innovations were surveyed from WEF (1994a), WEF (1994b), WEF (1995a), WEF (1995b), WEF (1996), Sieker and Verworn (Ed.) 1996, Ashley (Ed.) 1996, Bally et al. (Ed.) (1996), Henze et al. (1997), USEPA (1991a), and USEPA (1991b). An especially important summary of vacuum, pressure and small diameter gravity sewers is presented in USEPA (1991b).

Current Innovative Technologies - Review of Case Studies

Data Management, SCADA, Real Time Control

Many fields, including that of urban water management, have barely been able to keep up with the rapid technological and computational advances of the past decade. This has been exacerbated in the U.S. by the relative longevity of civil infrastructure works and the amount of infrastructure already in place, the majority being constructed in the 20th century. As the end of the project life of many of these works is approaching, and as new urban areas are being contemplated for certain high-growth sections of the U.S., practitioners and researchers in the field of urban water management have a unique window of opportunity. Now is the time to take advantage of the latest in technological advances and to use the past two decades as a model to predict what the future may bring in terms of technology.

The information age has changed the way in which resources are managed. This fact will be more apparent in new collection systems and waste management of the 21st century. New systems will be operationally data intensive due to a higher level of control. The current level of control in WWTPs may be seen as extending into the collection system. The increase in data quality and quantity will have positive effects on simulation for design, simulation for operation and for real time control of the system. These innovations should decrease costs and environmental impacts and maximize utility of the system.

Seattle, WA was one of the first major municipal sewer owners in the U.S. to use real time measurements of the collection system in a control scheme (Gonwa et al. 1994, Vitasovic et al. 1994). Vitasovic et al. (1994) describes the use of Real Time Control (RTC) in Seattle for CSO control purposes. Vitasovic (1994) states the goal of the program succinctly:

> **...*the idea behind RTC of CSO's is fairly straightforward: the conveyance system is controlled in real time with the objective of maximizing the utilization of in-line storage available within the system. The cost of the control system is often a fraction of the cost required for alternatives that include construction of new storage facilities*.**

The Seattle experience highlights the need for some form of system simulation to test control procedures off-line and to provide a higher level of system knowledge on-line than from data measurement alone (Vitasovic et al., 1994). A SCADA system provides automation one level above manual process level control and interfaces data retrieval systems with a relational database (Vitasovic et al., 1994, Dent and Davis 1995). Under the SCADA level of control, operators usually manage the system from a centralized location using Man-Machine Interface (MMI) software, receiving data from the SCADA while maintaining a supervisory level of control over the system (Vitasovic et al., 1994, Dent and Davis 1995). A higher level of automation may be used if a computer controller is used to change system operation. This can include simple control algorithms such as if-then and set-level points, or may be as advanced as providing on-line non-linear optimization (e.g., genetic algorithms).

Other successful applications of RTC in the U.S. include Lima, OH, Milwaukee, WI, and Cleveland, OH. Gonwa et al. (1994) provide a summary of the Milwaukee upgrade of an existing RTC. One new feature of the upgrade was additional control applied to the headwork's of the WWTP.

The hydraulic grade line of the Milwaukee system modified by the RTC upstream of the

WWTP resulted 1,5000,000m^3 inline storage volume during peak storm diversions to ISS after interceptor storage is maximized. In other words, the RTC provides control of the system to maximize pipe storage before diverting to the Inline Storage System. RTC is used in combination with storage facilities to minimize overflows.

Most applications of RTC, SCADA, automated system optimization and other advanced data management techniques are currently used in collection systems designed before the computer/information-age revolution. For new collection system designs, it is imperative that designers understand the physical/structural requirements of long-term high-quality data measurement. Successful designs will have adaptivity "built-in". The ability to change operational procedures as technological advances become available will greatly extend the useful life of future collection systems. In other words, future collection systems will have many critical "high information points" that, used in conjunction with control and simulation, will facilitate operating the system for optimal utilization. The tools used to accomplish this task will change during the project life of the system because of the longevity of infrastructure in contrast with the rapidity of computer technological advances. A successful design will anticipate these changes.

Sanitary Sewer Technology - Vacuum Sewers

Hassett (1995) provides a summary of current vacuum sewer technology. A typical vacuum sewer configuration is shown in Figure 6-7.

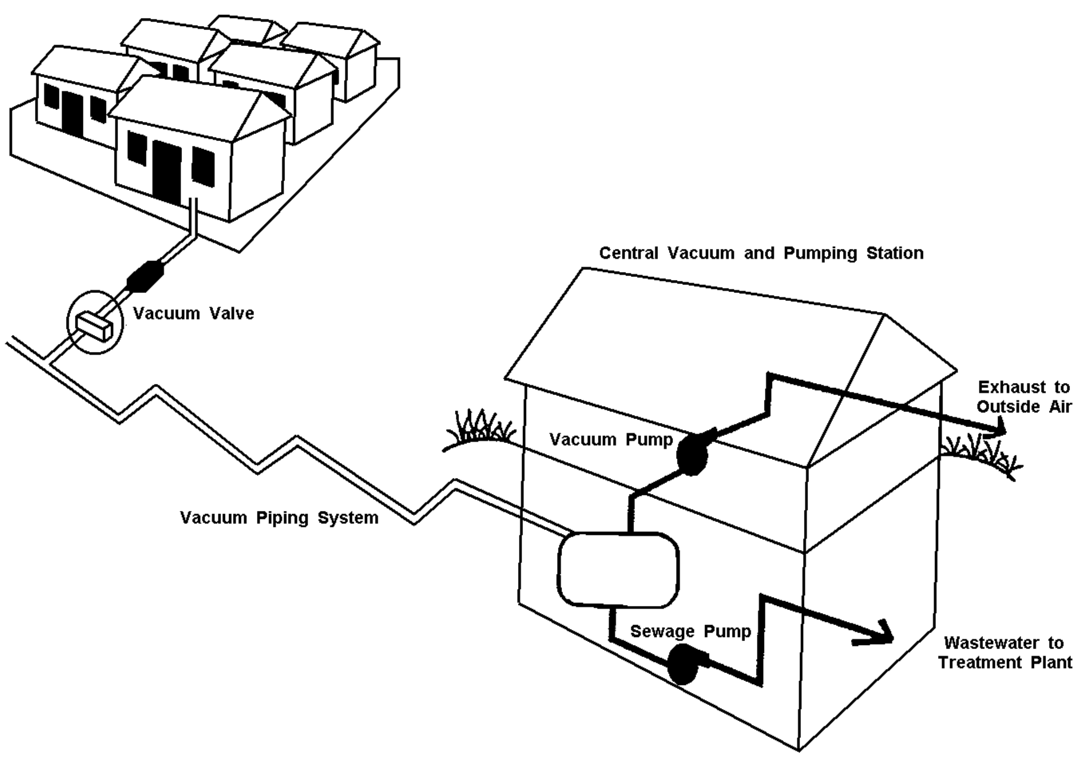

Figure 6-7. Typical vacuum sewer system schematic (Hassett 1995).

Vacuum sewers are typified by shallow pipelines that make them attractive for high-groundwater areas and for alignments that would require expensive rock excavation for gravity lines. Such systems are also useful in flat countries such as the Netherlands. Being completely sealed, vacuum lines also do not have any I/I - a remarkable benefit that begs the question: If vacuum sewer lines can be constructed water tight, why can't gravity lines? Vacuum systems do show promise, however, especially with recent advances in lifting capabilities. A recent installation in an Amtrak station in Chicago, IL used a valve configuration that achieved over 20 feet of vacuum lift (Hassett 1995). Another advantage of these systems is that vacuum toilets function with less than a third of water per flush than do modern low-flush toilets, using only 0.3 to 0.4 gallons per flush, compared with 1.5 to 6.0 gallons for toilets connected to gravity sewers.

Hassett (1995) provides a cost comparison for vacuum sewers for an actual project location in Virginia. The service area was assumed flat with a three foot depth-to-groundwater, an area of 750 acres (300 hectares), and approximately 750 residential units housing 3,000 people. The density was then varied to provide the construction cost information presented in Figure 6-8 and the operating costs shown in Table 6-8. Hassett (1995) notes that the operating costs of any of the system configurations is only 4 to 6% of the present value of the capital components and is, therefore, unlikely to be a decision factor. This observation may not be true in countries with higher energy costs.

Table 6-8. Annual operating costs of vacuum and gravity sewer systems as of 1995 (Hassett 1995).

Type of Sanitary Sewer System	Cost (1995 $U.S.)			
	Labor	Materials	Power	Total
Gravity (Dry)	26,000	3,000	4,000	33,000
Gravity (Wet)[1]	28,000	28,000	4,000	60,000
Modern Vacuum	42,000	10,000	8,000	60,000
High Lift Vacuum	34,000	3,000	8,000	45,000

(1) Wet means that the system includes lift stations and is below the water table.

A major advantage of these systems (along with pressure sewers) is their adaptability to monitoring and control. The use of pressure instead of gravity flow simplifies flow measurement. Control of these system is more exact than with gravity systems, thereby making them suited for overall system optimization by RTC.

Low Pressure Sewers

Another modern collection system technology that has been used in the U.S. is the low pressure sewer used in conjunction with a grinder pump (Farrell and Darrah 1994). These systems use a small grinder-pump typically installed at each residence. The grinder pump reduces solids to 1/4 to 1/2 inch maximum dimension (Farrell and Darrah

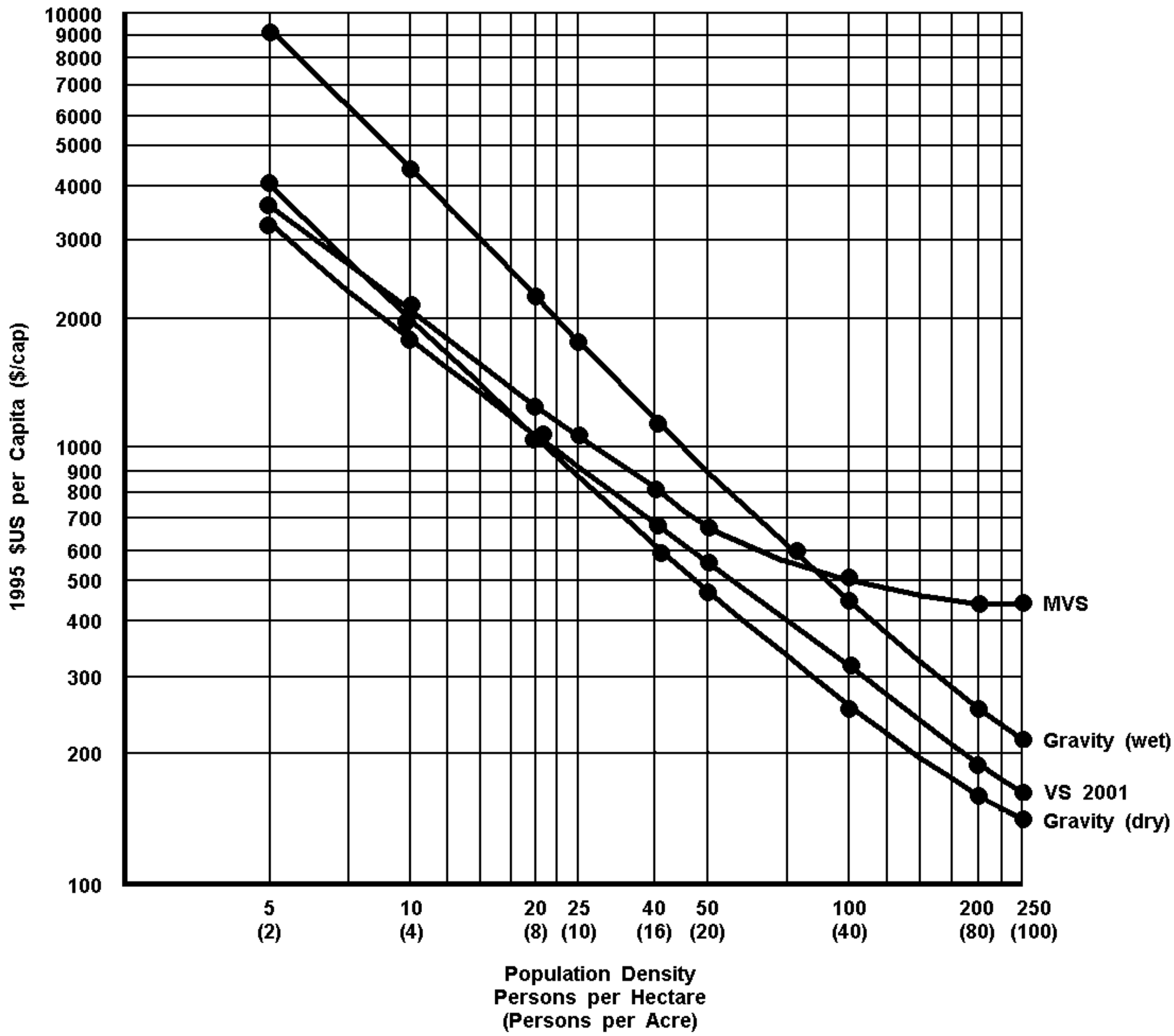

Figure 6-8. Per capita construction costs for different sanitary sewer systems at various population densities (Hassett 1995). (Note: MVS means modern vacuum system and VS 2001 represents 21st century vacuum system).

1994). Like vacuum systems, these low-pressure grinder systems feature water tight piping, thus virtually eliminating I/I. A full system in Washington County, MD went on-line in 1991. Water use, rainfall and wastewater flows were monitored and wastewater flows were found to be 110 to 130 gpcd, with no measurable increase during or following wet-weather events (Farrell and Darrah 1994).

A demonstration facility in Albany, NY was installed in 1972, where per capita flows were only 34 gpd. One purpose of this demonstration was to determine the effect of grinding solids on settleability. The conclusion was that there was no effect on settleability and treatability as compared with solids transported via a traditional gravity sewer (Farrell and Darrah 1994). Other demonstrations found no significant differences in grease concentrations (Farrell and Darrah 1994). The LPS pipe was excavated after several years of service, and no significant build-ups of solids were noted in the pipes (Farrell and Darrah 1994).

LPS systems have over a 20 year track record. As with most new technologies, engineers were hesitant to specify these sewers despite smaller capital expenditures due to the lack of long-term experience (Farrell and Darrah 1994). The reliability and costs of operating and maintaining the pumps were a major impediment to widespread use. Reliability of LPS systems has increased dramatically since the first commercial installation at a marina in the Adirondack mountains in NY (Farrell and Darrah 1994). In the 1972 Albany demonstration project (which only lasted 13 months), the mean time between service calls (MTBSC) for pump maintenance was 0.9 years (Farrell and Darrah 1994). An LPS system installed in 1986 in Bloomingdale, GA. averaged 10.4 years between service calls (Farrell and Darrah 1994) over an eight year period. Pump operation and maintenance (O&M) costs and MTBSC for five LPS collection systems are shown in Table 6-9 (Farrell and Darrah 1994).

Table 6-9. Pump data and O&M costs for low pressure sewer systems (Farrell and Darrah 1994).

Location	Number of Pumps	Average Age (years)	Annual O&M ($/pump)	MTBSC (years)
Cuyler, NY	41	17	53.00	4.6
Fairfield Glade, TN	955	16	36.07	5.6
Pooler/Bloomingdale, GA	998	11	13.24	10.4
Pierce County, WA	900	9	51.00	7.9
Sharpsburg/Keedysville, MD	780	5	18.00	>20

As with vacuum systems, LPS systems are well suited for control and monitoring due to the use of pressure rather than gravity to drive the system. This may be a significant advantage over gravity system in the future for RTC applications.

Small Diameter Gravity Sewers

These systems consist of a system of interceptor tanks, usually located on the property served, a network of small diameter collector gravity sewers (USEPA 1991b). The interceptor tanks remove settleable solids and grease from the wastewater. Effluent from each tank is discharged to the collector sewer via gravity or by pumping (septic tank effluent pumping (STEP)) (USEPA 1991b). A typical system layout is shown in Figure 6-9.

This system has the advantage of not having to transport appreciable solids (USEPA 1991b). Cost savings therefore result from having a lower required velocity and from less cleaning costs. Also, peak flows are attenuated in the tank. Therefore, the average to peak flow rate from wastewater is far less than for a standard gravity sewer (USEPA 1991b).

Otherwise, these systems function much the same as traditional gravity sewers. They have been used in rural areas to replace existing septic tank discharge. They are also used in developing countries to share costs (Mara, 1996) where they have been known as settled sewerage. A problem associated with these sewers is I/I. The use of old septic tanks tends to increase the amount of rainfall induced infiltration (USEPA 1991b).

Black Water/Gray Water Separation Systems

A more drastic break with modern systems is that of water separation at the household level. This has been a relatively active research area in recent years because of its appeal from a water conservation standpoint. Water from faucets, showers, dishwashers and clothes washers drains to a separate on-site filtration device. The filtered as water is then typically used for outdoor irrigation. This may be especially advantageous in arid areas where on-site stormwater detention for outdoor use does not meet the evapotranspiration needs on an average annual basis.

Waste/Source Separation

Recent research in Europe has focused on the separation of household waste in a variety of ways (Henze et al. (Ed.) 1997). The goal of these systems is to promote nutrient recycling and limit entropy gain (a goal for sustainability) via dilution. Urine separation is perhaps the most radical departure, where urine is tanked on site and converted to fertilizer (Hanaeus et al. 1997). Human urine contains 70% of the phosphorus and 90% of the nitrogen found in wastewater from toilets (Hanaeus et al. 1997). This technology is still in the formulation phase and has only been tested on a limited basis. Research shows it may have applicability for certain waste management applications.

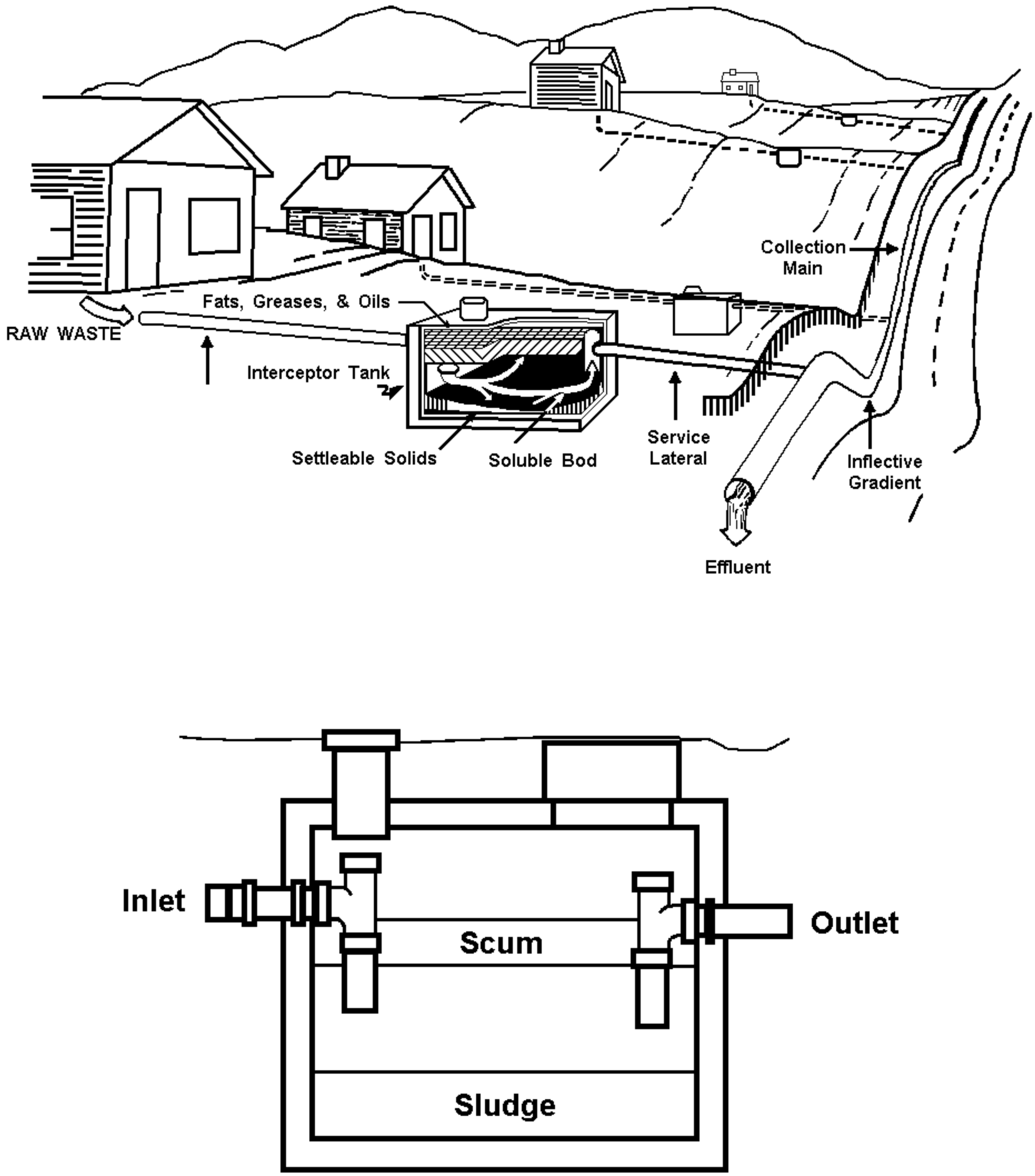

Figure 6-9. Components of small diameter gravity sewer (SDGS) system (USEPA 1991b).

Composting

On-site composting has been attempted at an ecovillage in Sweden (Fittschen and Niemczynowicz 1997). Toilet wastes were deposited in an on-site composting tank. The results of this experiment were less than desirable for a variety of reasons. The system is user-intensive, demanding a level of expertise beyond that of average residents. Technically it was only partially acceptable because the resulting compost was only of mediocre quality for agricultural use. The system was found to be socially unacceptable and was energy intensive as electricity was used to dry the compost (Fittschen and Niemczynowicz 1997). Again, this technology is in the testing phase, though it may hold promise for specific applications.

Combined Systems for the Future?

While old CSS are considered a major source of urban pollution, there is some recent activity in the area of new CSS. Where urban areas have significant amounts of NPS pollution that requires treatment, it may be possible to design a CSS to capture most of the annual storm volume for treatment at a WWTP, without discharging raw sewage during major events. Lemmen et al. (1996) describe a concept for a sewer system in the Netherlands that has connections between the storm drainage network and the sanitary collection system.

Walesh and Carr (1998) and Loucks and Morgan (1995) describe use of controlled storage of stormwater on and below streets to control surcharging and solve basement flooding in a CSS. The premise of this approach is that stormwater flow rate, not volume, is the principal cause of surcharging of CSS and resulting basement flooding and CSO. On and below street storage of stormwater, strategically placed throughout the CSS, reduces peak stormwater flows to rates that can be accommodated in the CSS without surcharging. The two large scale, constructed, and cost effective projects described by Walesh and Carr and by Loucks and Morgan were retrofits. However, the success of these projects suggests integrating the design of streets and CSS in newly developing high intensity areas.

Future Directions: Collection Systems of the 21st Century

New ideas for managing the entire urban water cycle in an integrated fashion are being formulated. This section synthesizes various aspects of recent research into a vision of what the near future may hold for collection systems in the 21st century. In order to synthesize these ideas, probable contextual factors within which collection systems will operate must be examined.

The definitive settlement type of the second half of the 20th century in the U.S. has been urban sprawl. In the U.S., this land use has been brought on largely by zoning and the proliferation of the automobile. Recent ideas regarding resource allocation seem to indicate that, while the automobile is not likely to disappear in this country in the next 50 years, its function may change. The “new urbanism” is likely to have mixed land use areas typified by neighborhoods where specific land use types may not dominate a specific urban catchment. Neighborhoods replace zoned land use types in the new urbanism and, as such, present a variety of opportunities for innovative urban water management.

The main premise of this discussion is that new urban development in the 21st century will begin to follow the patterns of the “new urbanism” in terms of land use and transportation. The other guiding premise is that design will be control-driven, that is to say that new systems will be designed to be controlled far beyond that which is presently used in wet-weather management. Therefore, the following scenarios describe possible future collection systems for new urban areas that integrate source control, system control, data management, life-cycle costs, environmental costs, and social acceptability.

Future Collection System Scenarios

High Density Areas

Areas with the highest levels of urban NPS will require stormwater treatment, much as they do today. A form of CSS, or an integrated storm-sanitary system (ISS) (Lemmen et al. (1996), will capture a large portion of the annual runoff volume from dense urban areas. Storm runoff will be reduced by source control and infiltration BMPs and the residual of small events will be transported to the WWTP. Large events will be throttled out of the ISS, before mixing with sanitary waste, and discharged to receiving waters. This new system will have the best of both CSS and separate systems. The advantage of the combined system has been treatment of small runoff producing events, including snowmelt. However, the disadvantage has always been the discharge of raw sewage to receiving waters during large events. With the advantage of control technology, as the sewers and/or the WWTP reach capacity, the stormwater is diverted directly to receiving waters, without mixing with sanitary and industrial wastes.

This system will have a high degree of built in control. The data stream begins with local radar observations. This information is combined with real-time ground level measurements of rainfall. These data will be used to predict the rainfall patterns over the catchment for the next half hour. The SCADA system receives information regrading the present state of the sanitary and storm portions of the waste stream. Quality as well as quantity are monitored. Performance of high rate treatment devices operating on the discharged stormwater is monitored. A critical innovation is the integration of the WWTP performance, operation and control into the system. Operation of the WWTP now extends to the collection system. Rainfall information in conjunction with the state of the system and receiving water data are used to predict potential outcomes of the wet-weather event using a system simulation model. Coupled with a non-linear optimization routine, an optimal control scheme is determined on-line and changes in system control are relayed back to the system via the SCADA system.

The system response is fed back to the SCADA and continuous control is maintained throughout the wet-weather event. This “feedback” loop provides the municipality with rapid response for flashy summer events and provides urban flood control simultaneously with water quality control. In addition, the time series of wet-weather data are now stored in a relational database, spatially segregated to interface with static geography stored in a GIS.

Suburban Development

Outlying from the new urban centers, suburban type development still exists. While less dense than the city, new suburban development contains some of the mixed land uses found in the urban center. The collection system serving this area is far different from the city, however, because the NPS pollution is not so severe as to warrant full treatment at the WWTP. BMPs and source control innovations have reduced the stormwater impacts on the receiving water. Regional detention is used for flood control and water quality enhancement while possibly providing recreation.

Sanitary wastes are transported via pressure sewers to collector gravity lines at the city's border. The use of pressure sewers has reduced suburban I/I to near zero. In addition, the new sanitary LPS sewers are very easy to monitor, as the age-old problem of open channel flow estimation is avoided by using pressure lines. This provides added certainty in the flow estimation and lends itself very well to control. Technology borrowed from the water distribution field has achieved a great level of system reliability and control. In fact, the sewer now mirrors the water distribution network, essentially providing the inverse service.

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